Source of vacuum electromagnetic zero-point energy

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Nature provides us with two alternatives for the origin of electromagnetic zero-point energy (ZPE): existence by fiat as part of the boundary conditions of the universe, or generation by the (quantum-fluctuation) motion of charged particles that constitute matter. A straightforward calculation of the latter possibility has been carried out in which it is assumed that the ZPE spectrum (field distribution) drives particle motion, and that the particle motion in turn generates the ZPE spectrum, in the form of a self-regenerating cosmological feedback cycle. The result is the appropriate frequency-cubed spectral distribution of the correct order of magnitude, thus indicating a dynamic-generation process for the ZPE fields.

INTRODUCTION

Quantum theory tells us that the vacuum is not field free, but is the seat of zero-point fluctuations (ZPF) of such fields as the vacuum-electromagnetic field, which is the focal point of our study here. Although there is still discussion as to whether the ZPF fields ought to be considered as "virtual" or "real,"[1] there is agreement that the ZPF fields lead to measurable physical consequences. One example is the very real Casimir force, the ZPF-induced quantum force between closely spaced metal plates.[2-5] The Casimir force results from changes in the normal-mode distribution (and hence in the associated vacuum-electromagnetic ZPF energy) as the distance between the plates changes.

Historically, there have been two schools of thought with regard to the source of the ZPF energy.[6] One suggestion is that the ZPF spectrum is a free field that is simply part of the passive boundary conditions of the universe, as is, for example, the 3-K cosmic background radiation left over from the big bang. A second hypothesis is that the ZPF spectrum is dynamically generated by the motion of charged particles throughout the universe which are themselves undergoing ZPF-induced motion, as part of a self-consistent cosmic feedback cycle. It is this second hypothesis that we explore here.

The basis of the second hypothesis is rather straightforward. Roughly, given charged particles in motion, an expected $1/r^2$ dependence of radiation due to such motion, and a $4\pi r^2 dr$ average volume distribution of such radiators in spherical shells about any given point, one could reasonably expect to find at any point a high-density radiation field (as in Olber's paradox). Zero-point energy provides just such a candidate field.

Further support for this hypothesis can be gleaned from the fact that absorption and reemission of ZPF radiation by a ZPF-driven dipole oscillator can be shown to be a local equilibrium process. That is, the radiation field generated by a ZPF-driven dipole just replaces that being absorbed from the ZPF background on a detailed balance basis, with regard to both frequency and angular distribution.[7] What remains to "close the loop," then, is to establish that this local equilibrium process is self-regenerating on the large scale; that is, that the local ZPF background experienced by a given charge is due to radiation from ZPF-induced charged-particle motion throughout the rest of the universe.

MATTER-ZPF INTERACTIONS

On the cosmological scale it is sufficient for our purposes to model the universe as a homogeneous distribution of matter in the form of hydrogen, the bulk of which is essentially ionized. To examine the origin of the ZPF background, we treat the interaction of matter with the ZPF on the basis of charged point particles interacting with a background of electromagnetic zero-point radiation with spectral-energy density:

$$\rho(\omega)\,d\omega=\frac{\hbar\omega^3}{2\pi^2c^3}d\omega\ , \tag{1}$$

which corresponds to an average energy $\frac{1}{2}\hbar\omega$ per normal mode.

Although assumed to be quantum mechanical in origin, the ZPF background can be treated as a collection of classical electromagnetic radiation modes with random phases. This treatment of quantum field-particle interactions on the basis of a classical ZPF, the so-called stochastic electrodynamics (SED) approach, constitutes a well-defined framework that has a long history of success in yielding precise quantitative agreement with full QED treatments of ZPF phenomena of the type being considered here.[8] It is therefore a convenient formalism for the study at hand.

The Fourier composition underlying the spectrum given in (1), which is homogeneous, isotropic, and Lorentz invariant, can be written as a sum over plane waves, viz, for the electric field

$$\mathbf{E}_{\mathrm{ZP}}(\mathbf{r},t)=\mathrm{Re}\sum_{\sigma=1}^{2}\int d^3k\,\hat{\epsilon}\left[\frac{\hbar\omega}{8\pi^3\epsilon_0}\right]^{1/2}e^{i\mathbf{k}\cdot\mathbf{r}-i\omega t+i\theta(\mathbf{k},\sigma)}\ ; \tag{2}$$

a similar expression for the magnetic field is obtained by replacing $\mathbf{E}_{\mathrm{ZP}}$ by $\mathbf{H}_{\mathrm{ZP}}$, $\hat{\epsilon}$ by $(\hat{\mathbf{k}}\times\hat{\epsilon})$, and ϵ_0 by μ_0. In these expressions $\sigma=1,2$ denote orthogonal polarizations, $\hat{\epsilon}$

and $\hat{\mathbf{k}}$ are orthogonal unit vectors in the direction of the electric field polarization and wave propagation vectors, respectively, $\theta(\mathbf{k},\sigma)$ are random phases distributed uniformly on the interval 0 to 2π (independently distributed for each $\mathbf{k},\sigma$), and $\omega=kc$.

Now, under the stated assumption that to first order the bulk of matter in the universe is taken to be in the form of hydrogen, which, furthermore, is ionized (or nearly so), we can to first order neglect binding force terms and consider the motions of the essentially free charge, electron or proton. Since the effects of interest in the end depend inversely on m^2, contributions due to proton motion are suppressed relative to those of electron motion by the factor $(m_e/m_p)^2$, where m_e and m_p are the electron and proton masses. We can therefore concentrate on electron motion alone.

We begin discussion of the interaction of electrons with the ZPF field on the basis of a point electron of mass m_e and charge l, immersed in the zero-point radiation given by (2). The (nonrelativistic) equation of motion, including radiation damping, is given by

$$m_e\ddot{\mathbf{R}}=\left[\frac{e^2}{6\pi\epsilon_0 c^3}\right]\dddot{\mathbf{R}}+e\mathbf{E}_{\mathrm{ZP}}\ , \tag{3}$$

where we neglect the magnetic force term $e\dot{\mathbf{R}}\times\mathbf{B}_{\mathrm{ZP}}$ in the nonrelativistic approximation. If we introduce the dipole moment $\mathbf{p}=e\mathbf{R}$, the damping constant $\Gamma=e^2/6\pi\epsilon_0 m_e c^3$, and $\Gamma'=6\pi\epsilon_0 c^3\Gamma$, we can rewrite the above in a form more convenient for the remaining discussion:

$$\ddot{\mathbf{p}}=\Gamma\dddot{\mathbf{p}}+\Gamma'\mathbf{E}_{\mathrm{ZP}}\ . \tag{4}$$

POYNTING'S THEOREM PROOF OF LOCAL EQUILIBRIUM

We turn our attention now to the fields generated by the ZPF-induced fluctuation motion in order to derive the important result that absorption and reemission of the ZPF field by free charge precisely reproduce the incident-ZPF field with regard to both frequency and angular distribution.

Considering, say, motion in the $\hat{\mathbf{p}}$ direction, we find that an assumed $e^{-i\omega t}$ time dependence substituted into (4) yields for the magnitude of any particular frequency component

$$\tilde{p}(\omega)=\frac{\Gamma'}{D}(\hat{\epsilon}\cdot\hat{\mathbf{p}})\tilde{E}_{\mathrm{ZP}}(\omega)\ , \tag{5}$$

where $D=-\omega^2-i\Gamma\omega^3$ and the tilde designates the magnitude of a frequency component. This expression can then be combined with the ZPF-field expression (2), and the standard oscillating dipole formulas[9]

$$\mathbf{E}_d(\omega)=\mathrm{Re}\left[\frac{1}{4\pi\epsilon_0}\tilde{p}e^{-i\omega t}\mathbf{G}\right], \tag{6}$$

$$\mathbf{H}_d(\omega)=\mathrm{Re}\left[\frac{c}{4\pi}\tilde{p}e^{-i\omega t}\mathbf{F}\right], \tag{7}$$

to yield expressions for the fields generated by the fluctuation motion. They are

$$\mathbf{E}_d=\mathrm{Re}\left[\frac{1}{4\pi\epsilon_0}\sum_{\sigma=1}^{2}\int d^3k\frac{\Gamma'}{D}\left[\frac{\hbar\omega}{8\pi^3\epsilon_0}\right]^{1/2}\times(\hat{\epsilon}\cdot\hat{\mathbf{p}})e^{-i\omega t+i\theta(\mathbf{k},\sigma)}\mathbf{G}\right], \tag{8}$$

and a similar expression for $\mathbf{H}_d$, obtained by multiplying the right-hand side of (8) by $c\epsilon_0$ and replacing $\mathbf{G}$ by $\mathbf{F}$, where, with $\hat{\mathbf{r}}$ a unit vector in the direction joining the charge to the field evaluation point,

$$\mathbf{G}=k^3e^{ikr}\left[(\hat{\mathbf{r}}\times\hat{\mathbf{p}})\times\hat{\mathbf{r}}\left[\frac{1}{kr}\right]+[3\hat{\mathbf{r}}(\hat{\mathbf{r}}\cdot\hat{\mathbf{p}})-\hat{\mathbf{p}}]\left[\frac{1}{(kr)^3}-\frac{i}{(kr)^2}\right]\right], \tag{9}$$

$$\mathbf{F}=k^3e^{ikr}(\hat{\mathbf{r}}\times\hat{\mathbf{p}})\left[\frac{1}{(kr)}+\frac{i}{(kr)^2}\right]. \tag{10}$$

Following the procedure established by Boyer for the harmonic oscillator case,[7] we calculate the average net Poynting vector associated with the ZPF-driven interaction from (2) and (8) as

$$\begin{aligned}\langle\mathbf{S}\rangle&=\langle\mathbf{E}\times\mathbf{H}\rangle=\langle(\mathbf{E}_{\mathrm{ZP}}+\mathbf{E}_d)\times(\mathbf{H}_{\mathrm{ZP}}+\mathbf{H}_d)\rangle\\&=\frac{\hbar c}{8\pi^3}\frac{1}{2}\mathrm{Re}\left\langle\sum_{\sigma=1}^{2}\sum_{\sigma'=1}^{2}\int d^3k\int d^3k'(\omega\omega')^{1/2}\exp[-i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}+i(\omega-\omega')t-i\theta(\mathbf{k},\sigma)+i\theta(\mathbf{k}',\sigma')]\right.\\&\qquad\left.\times(\mathbf{K}+\mathbf{L}+\mathbf{M}+\mathbf{N})\right\rangle,\end{aligned} \tag{11}$$

where

$$\mathbf{K}=\hat{\epsilon}\times(\hat{\mathbf{k}}'\times\hat{\epsilon}')\ ,$$

$$\mathbf{L}=\frac{1}{4\pi\epsilon_0}\frac{\Gamma'}{D(\omega')}(\hat{\epsilon}'\cdot\hat{\mathbf{p}})\hat{\epsilon}\times\mathbf{F}(k')e^{-i\mathbf{k}'\cdot\mathbf{r}}\ ,$$

$$\mathbf{M}=\frac{1}{4\pi\epsilon_0}\frac{\Gamma'}{D^*(\omega)}(\hat{\epsilon}\cdot\hat{\mathbf{p}})\mathbf{G}^*(k)e^{i\mathbf{k}\cdot\mathbf{r}}\times(\hat{\mathbf{k}}'\times\hat{\epsilon}')\ ,$$

$$\mathbf{N}=\left[\frac{1}{4\pi\epsilon_0}\right]^2\frac{\Gamma'^2}{D^*(\omega)D(\omega')}(\hat{\epsilon}\cdot\hat{\mathbf{p}})(\hat{\epsilon}'\cdot\hat{\mathbf{p}})\times\mathbf{G}^*(k)\times\mathbf{F}(k')e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}}\ .$$

Use of the complex conjugate (asterisk) and the notation $\frac{1}{2}\mathrm{Re}$ stems from the use of exponential notation. With

$\int d^3k \to \int d\Omega_k \int dk\, k^2$, and averaging over random phases given by

$$\langle \exp[-i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}+i(\omega-\omega')t-i\theta(\mathbf{k},\sigma) + i\theta(\mathbf{k}',\sigma')]\rangle = \delta_{\sigma\sigma'}\delta_{\omega\omega'}\delta(\mathbf{k}-\mathbf{k}') , \quad (12)$$

Eq. (11) can be simplified to

$$\langle \mathbf{S}\rangle = \frac{\hbar c}{8\pi^3}\tfrac{1}{2}\mathrm{Re}\left[\int dk\, k^2 \omega(\mathbf{K}'+\mathbf{L}'+\mathbf{M}'+\mathbf{N}')\right] , \quad (13)$$

where

$$\mathbf{K}' = \int d\Omega_k \left[\sum_{\sigma=1}^{2} \hat{\epsilon}\times(\hat{\mathbf{k}}\times\hat{\epsilon})\right] ,$$

$$\mathbf{L}' = -\frac{1}{4\pi\epsilon_0}\frac{\Gamma'}{D}\mathbf{F}\times\int d\Omega_k \left[\sum_{\sigma=1}^{2} \hat{\epsilon}(\hat{\epsilon}\cdot\hat{\mathbf{p}})e^{-i\mathbf{k}\cdot\mathbf{r}}\right] ,$$

$$\mathbf{M}' = \frac{1}{4\pi\epsilon_0}\frac{\Gamma'}{D^*}\mathbf{G}^*\times\int d\Omega_k \left[\sum_{\sigma=1}^{2} (\hat{\mathbf{k}}\times\hat{\epsilon})(\hat{\epsilon}\cdot\hat{\mathbf{p}})e^{i\mathbf{k}\cdot\mathbf{r}}\right] ,$$

$$\mathbf{N}' = \left[\frac{1}{4\pi\epsilon_0}\right]^2 \frac{\Gamma'^2}{|D|^2}\mathbf{G}^*\times\mathbf{F}\int d\Omega_k \left[\sum_{\sigma=1}^{2} (\hat{\epsilon}\cdot\hat{\mathbf{p}})^2\right] .$$

The angular integrations in k, given in Ref. 7, along with the use of such identities as $\mathrm{Re}(\mathbf{G}^*\times\mathbf{F})=\mathrm{Re}\mathbf{G}\times\mathrm{Re}\mathbf{F}+\mathrm{Im}\mathbf{G}\times\mathrm{Im}\mathbf{F}$, permit (13) to be further reduced to

$$\langle \mathbf{S}\rangle = \tfrac{1}{2}\int dk\, k^2 \frac{c}{4\pi}\frac{1}{4\pi\epsilon_0}\frac{\hbar\omega}{8\pi^3\epsilon_0} \times\left[\left[\frac{8\pi}{3}\frac{\Gamma'^2}{|D|^2}+4\pi\epsilon_0\frac{\Gamma'}{|D|^2}\frac{4\pi c^3}{\omega^3}\mathrm{Im}D\right] \times(\mathrm{Re}\mathbf{G}\times\mathrm{Re}\mathbf{F}+\mathrm{Im}\mathbf{G}\times\mathrm{Im}\mathbf{F})\right] . \quad (14)$$

Since, however, $\mathrm{Im}D=-\Gamma\omega^3$, the expression in large parentheses (and therefore the integrand) in (14) vanishes identically. Although derived for a single component of motion in the $\hat{\mathbf{p}}$ direction, this result holds independently for orthogonal components of motion as well, and therefore constitutes a general result for ZPF-driven charge motion.

It is to be noted that the vanishing of the integrand in this manner does not depend specifically on the power-law spectrum of the random radiation (which determines only the coefficient in the integrand), but rather only on the *isotropy* of the random radiation, as a result of which the angular integrations in k lead to a vanishing product term. This reflects the fact that any random radiation pattern (of which the ZPF distribution is a special case) is a stable equilibrium distribution under the conditions assumed here, despite the presence of a free particle, a result which parallels the linear dipole oscillator case.[7] An additional conclusion to be drawn from the vanishing of the integrand (and hence Poynting vector) is that the particle establishes an equilibrium exchange with the ZPF. In establishing this equilibrium, three factors come into play which should be noted. First, more detailed transient analysis shows that a free particle initially at rest in the ZPF exhibits a transient energy growth that results in a "jiggling" motion, but this results simply in a finite well-defined kinetic energy (set by a cutoff) that contributes to the (renormalized) mass.[10] Second, the possibility of a continual energy absorption from the ZPF which might lead to ever-increasing translational energies (a ZPF acceleration mechanism cited by Rueda as a possible source of cosmic ray energies[11]) has been shown to be quenched by an internal *Zitterbewegung*-type motion in the case of monopolar particles such as the electron of interest here.[12] Third, the detailed frequency balance in the Poynting vector calculation implied by the vanishing of the integrand at each and every frequency averages over a transient pumping of energy from one mode to another by a free particle since, again, detailed transient analysis shows that such frequency "sloshing" averages out over the cosmological time scales of interest here.[13]

Thus the significance of the vanishing of the integrand in the net Poynting vector calculation is that ZPF-driven motion results in an exchange between field and particle such that there is no average transfer of energy in any direction at any frequency. Thus the free-charge–ZPF interaction constitutes a local equilibrium process in which the random ZPF radiation pattern is self-regenerative.

ZPF-DRIVEN DIPOLE RADIATION

Now that it has been established that absorption and reemission of ZPF radiation by ZPF-driven charge motion is a local equilibrium process, it is of interest to determine the magnitude of that process. For this purpose we examine that component of the overall Poynting vector associated with the emission process alone, $\langle \mathbf{S}_d\rangle = \langle \mathbf{E}_d\times\mathbf{H}_d\rangle$. This component is given by the fourth term in (13). With the angular integration in k given by[7]

$$\int d\Omega_k \left[\sum_{\sigma=1}^{2} (\hat{\epsilon}\cdot\hat{\mathbf{p}})^2\right] = \frac{8\pi}{3} , \quad (15)$$

the fourth term becomes

$$\langle \mathbf{S}_d\rangle = \tfrac{1}{2}\mathrm{Re}\left[\frac{3\hbar c^4\Gamma^2}{4\pi^2}\int\frac{d\omega}{\omega}\frac{\mathbf{G}^*\times\mathbf{F}}{1+\Gamma^2\omega^2}\right] . \quad (16)$$

For frequencies up to well beyond electron-positron pair-production energies (which would take us into a relativistic regime beyond the scope of this paper), the second term in the denominator involving Γ^2 can be neglected relative to the first for electron parameters. With this taken into account, the energy density associated with the ZPF-driven dipole-generated flux $\langle u_d\rangle = |\langle \mathbf{S}_d\rangle|/c$ is given by

$$\langle u_d\rangle = \tfrac{1}{2}\mathrm{Re}\left[\frac{3\hbar c^3\Gamma^2}{4\pi^2}\int\frac{d\omega}{\omega}|\mathbf{G}^*\times\mathbf{F}|\right] . \quad (17)$$

Term-by-term evaluation of $(\mathbf{G}^*\times\mathbf{F})$ with the aid of (9) and (10) yields for the radiation-flux component $\propto 1/r^2$

$$(\mathbf{G}^*\times\mathbf{F})_{1/r^2} = \hat{\mathbf{r}}\left[\frac{\omega}{c}\right]^4\frac{\sin^2\psi}{r^2} , \quad (18)$$

where ψ is the angle measured from the dipole-motion unit vector $\hat{\mathbf{p}}$ to the evaluation-point unit vector $\hat{\mathbf{r}}$. Substitution of (18) into (17) then yields a radiation-component spectral density $\langle \rho_d \rangle = d\langle u_d \rangle / d\omega$

$$\langle \rho_d \rangle = \frac{3\hbar\Gamma^2\omega^3}{8\pi^2 c}\frac{\sin^2\psi}{r^2} . \tag{19}$$

The above expression, obtained on the basis of considering a single ($\hat{\mathbf{p}}$) component of motion, must be tripled to take into account contributions associated with three independent degrees of freedom as regards charge motion. Furthermore, of interest for the net contribution of a large collection of randomly oriented individual particle motions is an average over solid angle of individual contributions. With these considerations taken into account, by (19) the i^{th} particle contributes to the radiation-flux spectral density at a distance r from the particle an inverse square-law amount,

$$\rho_i(\omega) = 3\frac{1}{4\pi r^2}\int_0^{\pi}\langle \rho_d \rangle 2\pi r^2 \sin\psi\, d\psi = \frac{3\hbar\Gamma^2\omega^3}{4\pi^2 c r^2} . \tag{20}$$

COSMOLOGICAL DIPOLE RADIATION FLUX

As shown in the preceding section, ZPF-driven charge motion contributes to its surrounding environment a radiation flux given by (20). In summing the contributions from sources distributed over cosmological distances, we must take into account the expansion of the universe over time (with its corollary red shift of radiation arriving from distant sources), and the maximum distance (radius of communication) from which such contributions can be propagated since the big bang. In this section we shall limit our discussion to the class of cosmologies now thought to be correct, the so-called inflationary cosmologies.[14] In this case curvature vanishes, space becomes Euclidean in the large, and calculations involving the metric reduce to simple forms.

First, in an expanding universe of zero curvature we understand r in (20) to correspond to the comoving coordinate distance defined by[15]

$$r = a(t_r)\int_{t_e}^{t_r}\frac{c\,dt}{a(t)} , \tag{21}$$

where $a(t)$ is the scale factor tracking (model-dependent) cosmological expansion, and t_e and t_r are the times of emission and reception, respectively, of radiation propagating from emitter to receiver. The relationship between scale factors at the times of emission and reception are conveniently expressed in terms of the red-shift factor z by[16]

$$\frac{a(t_r)}{a(t_e)} = 1 + z . \tag{22}$$

As defined, r is both the radius of curvature of a two-sphere surrounding the emitter and passing through the receiver at the time of reception, and also the actual distance between emitter and receiver at the time of reception. Once an appropriate cosmological model has been chosen [scale factor $a(t)$ defined], (21) is solved to yield an expression for r in terms of the red-shift factor z, $r(z)$. As a special case, the radius of communication is given by

$$R_{\text{comm}} = \lim_{z\to\infty} r(z) . \tag{23}$$

Second, it can be shown by photon-counting arguments that for any spectral distribution $\rho(\omega)$ the ratio $\rho(\omega)/\omega^3$ is invariant under red shift from emitter to receiver, independent of the cause of the red shift (e.g., Doppler, cosmological, gravitational).[17] Therefore, with $\rho_i(\omega_r) = (\omega_r/\omega_e)^3\rho_i(\omega_e)$, (20) retains precisely its same form whether applied at the point of emission ($\omega=\omega_e$) or at the point of reception ($\omega=\omega_r$). The fact that the spectral distribution remains the same after suffering a red shift is unique to the ZPF spectrum with its cubic frequency dependence. This stands in contrast to, for example, the Planck 3-K cosmic background radiation which, although retaining the Planck form, differs following red shift by virtue of a drop in temperature of the form $T_r = T_e/(1+z)$.

We now wish to sum up the contributions from particles distributed throughout space, taking into account the fact that in an expanding universe radiation arriving from a particular shell located now ($t=t_r$) at a distance $r(z)$ was emitted at an earlier time t_e from a more compacted shell. With $\eta(t_e)$ the particle density of a particular shell at the time of emission, and $dV(t_e)$ the shell volume, the number of particles in that shell is given by $N = \eta(t_e)dV(t_e)$. As expansion takes place, the comoving volume element expands as $(1+z)^3$, while the particle density decreases as $1/(1+z)^3$, in accordance with the scale factor given by (22). Thus N remains constant as a result of the red-shift factor cancellations, as would be expected with no new material added to the shell.

Given that the individual particle contributions given by (20) are red-shift-independent, and the number of particles in a comoving volume element of a shell is also red-shift-independent, the summation of contributions from the various shells now located at $r(z)$ is given by the simple expression (for the case of zero-curvature inflationary cosmologies)

$$\rho = \int_0^{R_{\text{comm}}}\rho_i\eta 4\pi r^2 dr = \int_0^{\infty}\rho_i \eta 4\pi r(z)^2\frac{dr}{dz}dz , \tag{24}$$

where η and $4\pi r^2 dr$ are the particle density and volume element at the time of reception, and the range of integration is out to the radius of communication, or, equivalently, in the variable z, out to an infinite red-shift factor.

With ρ_i given by (20), (24) reduces to the form

$$\rho = 6\pi\Gamma^2 c^2 \eta R_{\text{comm}}\left[\frac{\hbar\omega^3}{2\pi^2 c^3}\right] . \tag{25}$$

In the hydrogen-filled universe postulated as our working model, η, the number of particles per unit volume effectively producing radiation (electrons) is related to the mass density ϕ by $\eta = \phi/m_p$, where m_p is the proton mass. As a result (25) becomes

$$\rho=\gamma\left[\frac{\hbar\omega^3}{2\pi^2c^3}\right], \quad (26)$$

$$\gamma\approx 0.04\phi(\mathrm{kg/m^3})R_{\mathrm{comm}}(\mathrm{m}), \quad (27)$$

where ϕ is in kg/m^3, R_{comm} is in meters, and the factor γ must be of order unity if the concept of a dynamically generated ZPF spectrum is to be consistent with observation.

As a first-order check on the magnitude of γ, we carry out a representative calculation using the Einstein–de Sitter inflationary model in which it is assumed that the cosmological constant vanishes, and that at all epochs the mass density ϕ is precisely equal to the critical density ϕ_c needed for closure.[18] Thus

$$\phi=\phi_c=\frac{3H^2}{8\pi G}, \quad (28)$$

where $H=(da/dt)/a$ is Hubble's constant, and $a(t)$ is the cosmological scale factor first mentioned here in connection with (21). In addition to theoretical arguments from inflationary cosmology, observational support for cosmologies approximating the Einstein–de Sitter model is provided by the measurements of Loh and Spillar on the number of galaxies versus red shift and flux.[19,20]

In the Einstein–de Sitter model, $Ht=\frac{2}{3}$ and $a(t)\propto t^{2/3}$. By use of these expressions in conjunction with (21) and (22) we find for the coordinate distance

$$r(z)=\frac{2c}{H}\left[1-\frac{1}{\sqrt{1+z}}\right], \quad (29)$$

from which by (23) we obtain

$$R_{\mathrm{comm}}=2c/H. \quad (30)$$

By current estimates $1/H$ is assumed to lie in the range 9–20 billion years, in which case (27)–(30) yield a range of values for $\gamma\sim 0.07-0.15$. Thus we find that a first-order calculation based on a reasonable choice of cosmology yields a result of roughly the correct order of magnitude to provide support for the concept that the vacuum electromagnetic zero-point energy is dynamically generated by charged-particle motions distributed throughout the universe. As uncertainties in cosmology are narrowed, this interpretation can be further tested on the basis of (27) which predicts that, for a value of γ precisely equal to unity, the average mass density ϕ (in kg/m^3) and radius of communication R_{comm} (in meters) are (for inflationary cosmologies) related by

$$\phi R_{\mathrm{comm}}\approx 25, \quad (31)$$

independent of the details of specific cosmological models.

If we inquire more deeply into the significance of a value of γ precisely equal to unity (that is, $6\pi\Gamma^2c^2\eta R_{\mathrm{comm}}=1$), we find (using the Einstein–de Sitter parameters) that it is equivalent to the statement $N_1=N_2$, where $N_1=e^2/4\pi\epsilon_0 G m_p m_e\sim 10^{39}$ is the ratio of electromagnetic to gravitational force between an electron and proton, and N_2 is the ratio of the Hubble distance $L_H=c/H$ to the diameter of the classical electron $d_0=e^2/2\pi\epsilon_0 m_e c^3$. From the standpoint of this paper such a "cosmological coincidence," often discussed in the context of Dirac's large-numbers hypothesis,[21] is seen to be a consequence of the cosmologically based ZPF-generation mechanism discussed here that links cosmological and atomic parameters.

DISCUSSION

As we have seen, a plausible argument can be made that the vacuum-electromagnetic ZPF fields are dynamically generated by the motion of charged particles. The assumption of a cosmological feedback cycle in which ZPF-induced particle motion establishes the ZPF field distribution, and vice versa, leads to an appropriate frequency-cubed spectral field distribution of the correct order of magnitude. As indicated by (31), the hypothesis is subject to a further test on the basis of continuing cosmological measurement.

Under the dynamic-generation hypothesis, the combination of ZPF-induced charge motion and ZPF field distribution can be seen as a kind of self-regenerating grand ground state of the universe. In contrast to other particle-field interactions, which result in transitions that continually alter particle-field occupation states, the ZPF interaction constitutes an underlying, stable "bottom rung" vacuum state in which further ZPF interaction simply reproduces the existing state on a dynamic-equilibrium basis. The vacuum state thus defined, it then constitutes an underlying energy matrix of fundamental importance in such diverse phenomena as atomic stability,[22,23] gravitation,[24] and the Casimir[2–5] and van der Waals[25] effects.

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[1]See Closing Remarks section in T. H. Boyer, Phys. Rev. D **29**, 1089 (1984). In addition, although the approach taken here is to assume the reality of the ZPF of the electromagnetic field, for completeness we note that an alternative viewpoint postulates that the results of field-particle interactions traditionally attributed to ZPF can also be expressed in terms of the radiation reaction of the particles involved, without explicit reference to the ZPF. For this viewpoint see P. W. Milonni, in *Foundations of Radiation Theory and Quantum Electrodynamics*, edited by A. O. Barut (Plenum, New York, 1980);

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